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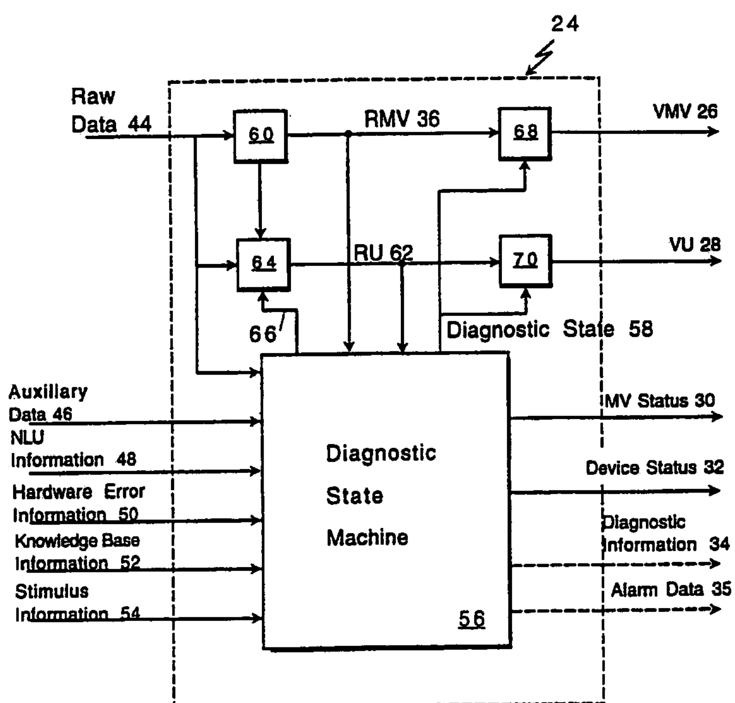

(57) Abstract

A sensor provides a measurement and information about the validity of the measurement. The sensor includes a transducer for generating a data signal related to the value of a variable and a transmitter for receiving the data signal and generating output signals. The transmitter generates a first output signal related to the value of the variable. The transmitter also generates a second output signal based on a dynamic uncertainty analysis of the first output signal.

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SELF-VALIDATING SENSORS

Background of the Invention

This invention relates to sensors and to control systems incorporating sensors.

A sensor generates measurement data. Typically, the measurement data is a signal that estimates the value of a process variable. In practice, the signal does not perfectly represent the value of the process variable. Instead, the signal also includes effects resulting from the sensor (such as sensor faults or distortion) and other process influences (including those attributable to "faulty" process behavior).

Sensor and control system designers employ numerous techniques to increase the reliability of measurement data. For example, sensor designers try to develop improved sensor designs that minimize both the occurrence of sensor faults and the distortions occurring during normal operation. In another approach, control system designers implement rigorous programs of sensor checking, maintenance, and calibration to reduce both the frequency at which sensor faults occur and the distortion caused by poorly maintained sensors.

In conjunction with increasing the reliability of measurement data, designers employ fault detection techniques to increase a control system's ability to recognize that measurement data is unreliable. For example, control system designers often rely on sensor redundancy to reduce the effect of any sensor fault that may occur. If measurement data from a sensor in a group of redundant sensors is inconsistent with measurement data from other sensors in the group, a control system can designate the inconsistent data as unreliable and ignore that data.

In another approach to fault detection, control systems monitor information about the process and the sensor for signs of sensor faults. Until recently, sensors have been limited to a single analog communication channel, normally based on the 4-20mA convention, and, therefore, have been unable to transmit signals other than a measurement data signal. Faced with this limitation, users of process fault detection techniques have tried to extract sensor and process fault information from measurement data. However, in attempting to minimize distortion of the measurement data, sensor designers have tried to eliminate, by sophisticated filtering and other means, every component of the measurement data signal that does not actually relate to the variable being measured. Thus, improved sensor designs have limited the information available for extraction from the measurement signal for fault detection purposes.

Recent use of digital communications technology by control system designers has enabled sensors to transmit multiple signals. This, in combination with internal diagnostics generated by microprocessors, which are now commonly embedded within sensors, has resulted in sensors that are able to perform fault detection analyses internally and transmit the results of these analyses as a fault information signal. Typically, the fault information signal is either a device specific error code or a single bit which indicates that the sensor is either functional or nonfunctional.

Summary of the Invention

The invention provides a self-validating sensor for use in process control systems. A self-validating sensor provides, based on all information available to the sensor, a best estimate of the value of a parameter being monitored. Because the best estimate is based, in

part, on nonmeasurement data, the best estimate does not always conform to the value indicated by the current, possibly faulty, measurement data. A self-validating sensor also provides information about the uncertainty and reliability of the best estimate, as well as information about the operational status of the sensor. Uncertainty information is derived from known uncertainty analyses and is provided even in the absence of faults.

In one aspect, generally, the invention features a sensor that includes a transducer that generates a data signal related to the value of a variable and a transmitter that receives the data signal and generates output signals in response. The transmitter generates a first output signal related to the value of the variable and a second output signal based on a dynamic uncertainty analysis of the first output signal. When the sensor experiences a fault, the transmitter modifies the first and second output signals to account for the impact of the fault. In some embodiments, the transmitter generates a third output signal that indicates a state of reliability of the first output signal.

The second output signal, which provides on line uncertainty, can be used for data quality management. A specified maximum permitted uncertainty can be used, for example, in specifying plant instrumentation, supervising feedback control, scheduling maintenance, and demonstrating adequate data quality for environmental compliance or custody transfer applications.

Generally, the invention provides a standard, device-independent method of communicating sensor faults and measurement quality, which eases integration into control schemes. In some cases, this avoids the cost of sensor redundancy and constant calibration programs, which, in any large or complicated process plant, are quite costly and of dubious value.

The invention also eases implementation of fault detection schemes by supplying a common set of variables in a generic form for use by control systems and requiring sensor designers, who are in the best position to recognize and define faulty behavior, to implement the actual fault detection in the sensors themselves.

Brief Description of the Drawing

Fig. 1 is a block diagram of a process control system with multiple sensors and actuators.

Fig. 2 is a block diagram of a sensor according to the invention.

Fig. 3 is a block diagram showing the flow of information in the sensor of Fig. 2.

Fig. 4 is a composite graph showing three methods of responding to a fault in the sensor of Fig. 2.

Fig. 5 is a composite graph of various signals produced by the sensor of Fig. 2 versus time.

Fig. 6 is a block diagram showing the timing of information flow in the sensor of Fig. 2.

Fig. 7 is a block and schematic diagram of a temperature sensor according to the invention.

Fig. 8 is a set of composite graphs of an auxiliary signal (upper graph), raw temperature (middle graph), and validated temperature and uncertainty (lower graph) versus time for the instrument of Fig. 7.

Fig. 9 is a set of composite graphs of raw data (upper graph), raw temperature (middle graph) and validated temperature and uncertainty (lower graph) versus time for the instrument of Fig. 7.

Fig. 10 is a paired composite graph of auxiliary data (upper graph) and validated temperature and uncertainty (lower graph) for the instrument of Fig. 7.

Fig. 11 is a schematic and block diagram of a Coriolis flow meter.

Fig. 12 is pseudocode showing steps performed by the meter of Fig. 11 during each sampling period.

Fig. 13 is pseudocode showing steps performed by the meter of Fig. 11 in determining temperature and associated uncertainty.

Fig. 14 is pseudocode showing steps performed by the meter of Fig. 11 in diagnosing a fault.

Fig. 15 is a set of composite graphs showing the effect of a loss of temperature on temperature (upper graphs), density (middle graphs) and mass flow rate (lower graphs) versus time for the meter of Fig. 11.

Description of the Preferred Embodiments

Referring to Fig. 1, in a process control system 10, a plurality of sensors 12 monitor parameters of a process 14 and provide signals about the monitored parameters to a data control and management system 16 on a digital communications link 18. Digital communications link 18 allows bidirectional communication between multiple central processing units 16, sensors 12, and process actuators 20. In response to signals from sensors 12, data control and management system 16 sends process control signals to process actuators 20 on digital communications link 18. Thereafter, process actuators 20 respond to process control signals from data control and management system 16 by modifying parameters of process 14.

Because data control and management system 16 relies on measurement signals from sensors 12 in controlling process 14, measurement signals from sensors 12 need to be accurate and reliable. A given sensor 12 typically cannot guarantee complete accuracy and reliability; instead, sensor 12 provides data control and management system 16 with indications of the uncertainty (which, in turn, indicates the accuracy) and the reliability of the measurement signals.

Referring also to Fig. 2, sensor 12 includes one or more transducers 22 that monitor the values of parameters of process 14 and provide signals to a transmitter 24. Transmitter 24 samples the signals from transducers 22 and produces measurement values for the parameters being monitored by transducers 22. Transmitter 24 validates the measurement values and provides the validated measurement values, along with an indication of the uncertainty of the validated measurement values, to data control and management system 16 via digital communications link 18. In addition, transmitter 24 generates signals indicating the reliability of the validated measurement values provided by sensor 12 and the operational status of sensor 12, and provides these signals to data control and management system 16 via digital communications link 18.

Transmitter 24 generates the signals provided to data control and management system 16 during a sample period and transmits the signals at the end of the sample period. Typically, the duration of a sample period is less than one second, but this duration can be adjusted as required by a particular application.

As shown in Fig. 3, transmitter 24 typically provides four signals to data control and management system 16:

(1) VMV 26 - a validated measurement value of a process parameter (transmitter 24's best estimate of the value of the measured parameter),

(2) VU 28 - a validated uncertainty associated with VMV 26,

(3) MV status 30 - the status of VMV 26 (the manner in which VMV 26 was calculated), and

(4) device status 32 - the operational status of the sensor.

If sensor 12 measures multiple process parameters, transmitter 24 produces a version of VMV 26, VU 28, and MV status 30 for each process parameter.

In some circumstances, transmitter 24 can provide additional information. For example, upon a request by data control and management system 16, transmitter 24 provides detailed diagnostic information 34 about the status of sensor 12. Also, when a measurement has exceeded, or is about to exceed, a predetermined limit, transmitter 24 can send alarm data 35. Typically, different alarm levels can be used to indicate the severity with which the measurement has deviated from the predetermined value.

VMV 26 and VU 28 are numeric values. For example, VMV 26 could be a temperature measurement valued at 200 degrees and VU 28, the uncertainty of VMV 26, could be 9 degrees. In this case, there is a high probability (typically 95%) that the actual temperature being measured falls within an envelope around VMV 26 and designated by VU 28 (191 degrees to 209 degrees).

Transmitter 24 generates VMV 26 based on a signal produced by transducer 22. First, transmitter 24 derives RMV 36, an unvalidated image of the measured process parameter that is based on the signal generated by transducer 22. Typically, when transmitter 24 detects no abnormalities in sensor 12, transmitter 24 has nominal confidence in RMV 36 and sets VMV 26 equal to RMV 36.

As discussed in more detail below, when transmitter 24 detects an abnormality in sensor 12, transmitter 24 does not set VMV 26 equal to RMV 36. Instead, transmitter 24 sets VMV 26 to a value that transmitter 24 considers to be a better estimate of the actual parameter than RMV 36. If transmitter 24 detects a fault in sensor 12 that only partially affects the reliability of RMV 36 such that transmitter 24 has

reduced confidence in RMV 36, transmitter 24 typically rederives RMV 36 by modifying the parameters used in deriving RMV 36 to account for the fault, and sets VMV 26 equal to the new value of RMV 36. Alternatively, if transmitter 24 detects a fault in sensor 12 which indicates that RMV 36 bears no relation to the actual measured value such that transmitter 24 has zero confidence in RMV 36, transmitter 24 sets VMV 26 to a value based on past performance.

Referring also to Fig. 4, three examples of past performance values include short term past values, long term past values, and a combination of long and short term past values. As shown in (a), when short term past values are used, VMV 26 can equal the value of VMV 26 had immediately prior to the fault that occurs at time 5. As shown in (b), when long term past value are used, VMV 26 can equal the average value of VMV 26. As shown in (c), when a combination of long and short term past values is used, the long and short term past values can be combined using the following equation, which weighs each value according to its uncertainty:

$$VMV_{L\&S} = \frac{VU_L^2}{VU_L^2 + VU_S^2} * VMV_S + \frac{VU_S^2}{VU_L^2 + VU_S^2} * VMV_L$$

where VU_L and VU_S are the long and short term past values for VU 28 and VMV_L and VMV_S are the long and short term past values for VMV 26.

Transmitter 24 generates VU 28 based on a raw uncertainty signal, RU 62, that is the result of a dynamic uncertainty analysis of RMV 36. Transmitter 24 performs this uncertainty analysis during each sampling period. Uncertainty analysis, originally described in "Describing Uncertainties in Single Sample Experiments," S.J. Kline & F.A. McClintock, <u>Mech. Eng.</u>, 75, 3-8 (1953), has been widely applied and has achieved the status of an international standard for calibration. Essentially, an

uncertainty analysis provides an indication of the "quality" of a measurement. Every measurement has an associated error, which, of course, is unknown. However, a reasonable limit on that error can often be expressed by a single uncertainty number (ANSI/ASME PTC 19.1-1985 Part 1, Measurement Uncertainty: Instruments and Apparatus).

As described by Kline & McClintock, for any observed measurement M, the uncertainty in M, w_M, can be defined as follows:

$$M_{true} \in [M - w_M, M + w_M]$$

where M is true (M_{true}) with a certain level of confidence (typically 95%). This uncertainty is readily expressed in a relative form as a proportion of the measurement (i.e. w_M/M).

A propagation rule exists for obtaining the uncertainties of arbitrary functions of primary measurements. For example, for an arbitrary function R of variables X, Y, and Z,

$$R = R(X,Y,Z)$$

the uncertainty of R is given by

$$[w_R/R]^2 = [\partial R/\partial X]^2 \; [w_X/R]^2 + [\partial R/\partial Y]^2 \; [w_Y/R]^2 + [\partial R/\partial Z]^2 \; [w_Z/R]^2$$

This sum of squares form is derived from the Taylor series, and assumes the independence of X, Y, and Z, that their relative uncertainties are "small", and that all uncertainties are expressed at the same probability level. For purposes of this application, all uncertainties are assumed to be at 95% probability.

One of the uses of the uncertainty propagation formula is to reveal particular circumstances that can result in a higher or lower than expected level of uncertainty. For example, as discussed in S.J. Kline, "The Purposes of Uncertainty Analysis", ASME Journal of

Fluids Engineering, Vol. 107, No. 2, pp. 153-160, 1985, if R is calculated from x and y using the equation

$$R = x - y,$$

the uncertainty in R, w_R, is given by

$$w_R/R = [(x/(x-y) * w_x/x)^2 + (y/(x-y) * w_y/y)^2]^{1/2}.$$

If x = 1.0, y = 0.98, and the uncertainty in both x and y is 1%, then the uncertainty in R is:

$$w_R/R = [(1/0.02 * 0.01)^2 + (0.98/0.02 * 0.01)^2]^{1/2}$$
$$= 0.700 = 70\%.$$

By comparison, if R is calculated from a variable z using the equation

$$R = (1/(1 + z))^{1/2},$$

the uncertainty in R is given by

$$w_R/R = w_z/2(1 + z).$$

If z = 0.1 and the uncertainty is z is 20%, then the uncertainty in R is only 0.91%.

On reflection these results should not be surprising. In the first example, two quantities of similar magnitude are being subtracted, which will increase the relative error in the result. In the second, although z has a large uncertainty, its influence on R is relatively small. Of course, for different values of x, y, and z, the impact of their uncertainties will vary. Uncertainty analysis is useful in that it can quantify these effects.

Returning to Fig. 3, VU 28 has a non-zero value even under ideal conditions (i.e., a faultless sensor operating in a controlled, laboratory environment). This is because the measurement produced by a sensor is never completely certain and there is always some potential for error.

As with VMV 26, when transmitter 24 detects no abnormalities in sensor 12, transmitter 24 sets VU 28 equal to RU 62. When transmitter 24 detects a fault in sensor 12 that only partially affects the reliability of

RMV 36, transmitter 24 typically performs a new uncertainty analysis that accounts for effects of the fault and sets VU 28 equal to the results of this analysis. As with VMV 26, transmitter 24 sets VU 28 to a value based on past performance when transmitter 24 determines that RMV 36 bears no relation to the actual measured value.

Fig. 4 illustrates three exemplary techniques for adjusting VU 28 based on past performance values. First, as shown in (a), VU 28 can be increased during each sampling period by the maximum observed rate of change of VMV 26. This technique, which tends to give good short term results, eventually produces unrealistic values for VU 28. Next, as shown in (b), when VMV 26 is set equal to the long term average of VMV 26, VU 28 can indicate that VMV 26 can take any previous value of VMV 26. Thus, if VMV 26 always falls between 0 and 100 and VMV 26 is set to 50, VU 28 is set to 50. This technique tends to give unduly pessimistic short term results, but avoids the long term problems of method (a). Finally, as shown in (c), when VMV 26 is based on a combination of the long and short term past values for VMV 26, VU 28 can be calculated as follows:

$$VU_{L\&S} = \frac{VU_L * VU_S}{(VU_L^2 + VU_S^2)^{1/2}}$$

where VU_L and VU_S are the long and short term past values for VU 28.

To ensure that data control and management system 16 uses VMV 26 and VU 28 properly, MV status 30 provides information about how VMV 26 and VU 28 were calculated. Transmitter 24 produces VMV 26 and VU 28 under all conditions--even when transducers 22 are inoperative. Often, data control and management system 16 needs to know whether VMV 26 and VU 28 are based on "live" or historical data. For example, if data control and

management system 16 were using VMV 26 and VU 28 in feedback control and transducers 22 were inoperative, data control and management system 16 would need to know that VMV 26 and VU 28 were based on past performance.

MV status 30 is based on the expected persistence of any abnormal condition and on the confidence of transmitter 24 in RMV 36. The four primary states for MV status are generated according to Table 1.

Table 1

Expected Persistence	Confidence in RMV	MV Status
not applicable	nominal	CLEAR
not applicable	reduced	BLURRED
short	zero	DAZZLED
long	zero	BLIND

A CLEAR MV status 30 occurs when RMV 36 is within a normal range for given process conditions. A DAZZLED MV status 30 indicates that RMV 36 is quite abnormal, but the abnormality is expected to be of short duration. Typically, transmitter 24 sets MV status 30 to DAZZLED when there is a sudden change in the signal from transducer 22 and transmitter 24 is unable to clearly establish whether this change is due to an as yet undiagnosed sensor fault or to an abrupt change in the variable being measured. A BLURRED MV status 30 indicates that RMV 36 is abnormal but reasonably related to the parameter being measured. For example, transmitter 24 may set MV status 30 to BLURRED when RMV 36 is a noisy signal. A BLIND MV status 30 indicates that RMV 36 is completely unreliable and the fault is expected to persist.

Two additional states for MV status 30 are UNVALIDATED and SECURE. MV status 30 is UNVALIDATED when

transmitter 24 is not performing validation of VMV 26. MV status 30 is SECURE when VMV 26 is generated from redundant measurements in which transmitter 24 has nominal confidence.

Device status 32 is a generic, discrete value summarizing the health of sensor 12 that is used primarily by fault detection and maintenance systems. Typically, device status 32 is in one of six states, each of which indicates a different operational status for sensor 12. These states are: GOOD, TESTING, SUSPECT, IMPAIRED, BAD, or CRITICAL. A GOOD device status 32 means that sensor 12 is in nominal condition. A TESTING device status 32 means that sensor 12 is performing a self check, and that this self check may be responsible for any temporary reduction in measurement quality. A SUSPECT device status 32 means that sensor 12 has produced an abnormal response, but transmitter 24 has no detailed fault diagnosis. An IMPAIRED device status 32 means that sensor 12 is suffering from a diagnosed fault that has a minor impact on performance. A BAD device status 32 means that sensor 12 has seriously malfunctioned and maintenance is required. Finally, a CRITICAL device status 32 means that sensor 12 has malfunctioned to the extent that sensor 12 may cause (or have caused) a hazard such as a leak, fire, or explosion.

Fig. 5 illustrates an example of the relationship between VMV 26, VU 28, MV status 30, and RMV 36. In another aspect, Fig. 5 illustrates a preferred method of displaying the relationship between VMV 26 and VU 28 both during normal operation and when a fault has occurred: VU 28 is shown both as a separate signal and as an envelope surrounding VMV 26 (line 38 indicates the sum of VMV 26 and VU 28 and line 40 indicates the difference between VMV 26 and VU 28). When VU 28 is expressed as an

envelope surrounding VMV 26, a user can, by examining the envelope, visually determine the range of probable values of the parameter represented by VMV 26 for any displayed time.

In the region between time T1 and time T2, RMV 36 is a periodic signal whose amplitude falls within an expected range. In this region, VMV 26 equals RMV 36, MV status 30 is CLEAR, and VU 28 remains at a constant "normal" level that corresponds to RU 62, the uncertainty under normal operating conditions (with line 42 representing a zero value for VU 28). For purposes of this example, RU 62 is assumed to have a constant value.

At time T2, RMV 36 begins to increase at a rate that substantially exceeds an expected rate of change for RMV 36. Transmitter 24 takes a number of actions in response to this unexplained phenomenon. First, transmitter 24 changes MV status 30 to DAZZLED. Next, transmitter 24, which is basing VMV 26 and VU 28 on short term past performance values in this example, maintains VMV 26 at the value that VMV 26 had just before the sudden increase in RMV 36 at time T2. Finally, transmitter 24 begins to increase VU 28 at a constant rate that equals the maximum rate of increase of VMV 26 during normal operation. The progressive increase in the value of VU 28 over time reflects increasing uncertainty of the value of the measurement in the absence of up to date valid transducer data caused by sensor 12 being DAZZLED.

RMV 36 continues to increase until time T3. At time T3, RMV 36 stops increasing and remains at a constant level. Because the value of RMV 36 now exceeds expected values, transmitter 24 does not change VMV 26 or MV status 30, and continues to increase VU 28 at a constant rate. At time T4, RMV 36 begins to decrease. Because the value of RMV 36 still exceeds expected

values, transmitter 24 makes no changes to VMV 26 or MV status 30, and continues to increase VU 28 at a constant rate.

At time T5, RMV 36 begins to operate as expected. In response, transmitter 24 changes MV status 30 to BLURRED and begins to merge VMV 26 with RMV 36 using, for example, the following equation:

$$VMV_{n+1} = 0.95 * VMV_n + 0.05 * RMV_{n+1}$$

where VMV_{n+1} is the value of VMV 26 for the current sample, VMV_n is the value of VMV 26 generated in the previous sample, and RMV_{n+1} is the value of RMV 36 for the current sample. Next, transmitter 24 initializes a recovery timeout period. Finally, transmitter 24 begins to decrease VU 28 by merging VU 28 with RU 62 using, for example, the following equation:

$$VU_{n+1}^2 = 0.95^2 * VU_n^2 + 0.05^2 * RU_{n+1}^2$$

where VU_{n+1} is the value of VU 28 for the current sample, VU_n is the value of VU 28 generated in the previous sample, and RU_{n+1} is the value of RU 62 for the current sample.

At time T6, transmitter 24 determines that the recovery timeout period has expired and changes MV status 30 to CLEAR. Because transmitter 24 now has nominal confidence in RMV 36, transmitter 24 sets VU 28 equal to RU 62.

If, at time T5, RMV 36 had not returned to expected levels, sensor 12 would have either maintained MV status 30 as DAZZLED or diagnosed a sensor fault and changed MV status 30 to BLIND. MV status 30 can only be DAZZLED for a limited "timeout" period. Thus, if RMV 36 remained at unexpected levels, the timeout period would eventually expire, and transmitter 24 would change MV status 30 to BLIND.

As shown in Fig. 3, transmitter 24 uses several sources of information, each of which is discussed below,

in generating VMV 26, VU 28, MV status 30, device status 32, diagnostic information 34, and alarm data 35. Raw data 44, the basic measurement information available to transmitter 24, is typically an electrical image of the output of one or more transducers 22 (e.g., the frequency of oscillation or the resistance of a transducer 22). Raw data 44 contains the maximum information available about the response of transducer 22 and is therefore a rich source of information for statistical tests to detect sensor faults. However, knowledge of expected process behavior cannot be applied readily to raw data 44 and is more appropriately applied to statistics based on RMV 36.

Because RMV 36 directly relates to a process parameter (e.g., temperature or mass flow rate), transmitter 24 can link the expected (no-fault) behavior of RMV 36 to the expected behavior of the process parameter associated with RMV 36. Transmitter 24 derives RMV 36 from raw data 44 by conventional processing. For example, if raw data 44 corresponds to the resistance of a transducer 22 and RMV 36 corresponds to temperature, transmitter 24 derives RMV 36 based on raw data 44 in light of known effects of temperature on the resistance of transducer 22. Often, transmitter 24 filters RMV 36 to reduce the effect of sensor noise and high frequency process disturbances. When filtering occurs, RMV 36 contains less information than raw data 44.

To a certain extent, raw data 44 and RMV 36 are complementary sources of information. While raw data 44 has more information content than RMV 36, RMV 36 is more easily compared with expected process behavior. Thus, raw data 44 and RMV 36 each offer useful information to transmitter 24.

Auxiliary data 46 is provided by auxiliary signals within sensor 12. Auxiliary signals, though not directly

related to raw data 44 or RMV 36, give useful information about the health or performance of sensor 12. For example, statistical tests to identify characteristic sensor or process behavior may be associated with particular auxiliary signals. Examples of auxiliary signals include the electrical properties of components within sensor 12 (e.g., signal levels at the input or output stages of power amplifiers) and hardware error information 50. Hardware error information 50 is a special, preprocessed form of auxiliary information generated by digital components within sensor 12, requiring little or no processing or interpretation. For example, a memory checksum error in a memory component of transmitter 24 would constitute hardware error information 50.

In addition to information from within sensor 12 or from process 14, transmitter 24 uses information from data control and management system 16 in generating output signals. Data control and management system 16 is known as the "Next Level Up" ("NLU"), and information from data control and management system 16 is known as NLU information 48. A difficulty associated with having transmitter 24 validate the output of sensor 12 is that transmitter 24 may have insufficient information to reach a valid conclusion. For example, transmitter 24 may be unable to distinguish between certain types of sensor faults (e.g., drift errors that cause the output of the sensor to change over time for a given input) and legitimate process changes. In these situations, transmitter 24 may refer to NLU information 48 for clarification. Data control and management system 16, which has access to additional information, including data from other sensors 12, provides transmitter 24 with the information needed to distinguish between process changes and sensor drift.

Transmitter 24 may request NLU information 48 such as anticipated process limits through standard requests to data control and management system 16. Alternatively, data control and management system 16 can provide unsolicited information, such as indications of changes in process behavior that will change the process parameters being measured by transducers 22, to transmitter 24. For example, if process 14 operates in a number of phases that each have distinct characteristics, data control and management system 16 can notify transmitter 24 when the phase of process 14 changes.

Application knowledge base information 52 allows transmitter 24 to estimate a "wear and tear" effect on sensor performance. Application knowledge base information 52 describes the relationship between signals and sensor characteristics over time. In some applications, sensors are known to degrade much more rapidly under certain conditions (e.g., at extremes of their operating range). For example, if a normal range pH probe is exposed to more than about 12pH for as little as an hour, the probe may become alkali-conditioned and fail to respond when the solution becomes more acidic. Application knowledge base information 52 also includes factors such as the time elapsed since the last calibration or last maintenance of sensor 12.

Sensor/process stimulus information 54 provides information about a known stimulus applied to the process or part of a sensor. Sensor/process stimulus information 54 is used in implementing procedures for testing sensor 12. A known stimulus is applied to process 14 or sensor 12 and the response generated by sensor 12 is compared with an expected response. For example, sensor/process stimulus information 54 could describe a known force that has been introduced to a pressure transducer. Sensor/process stimulus information 54 is generated by

transmitter 24 (i.e., as part of a self-test initiated by transmitter 24) or sent by data control and management system 16 as NLU information 48. When testing disables the measuring capability of sensor 12, transmitter 24 sets the MV status 30 of each disabled measurement to DAZZLED, bases VMV 26 and VU 28 on past performance, and sets device status 32 to TESTING.

Fig. 3 also shows the functional units of transmitter 24. A diagnostic state machine 56 processes all of the information available to transmitter 24 and determines the diagnostic state 58 of sensor 12. Diagnostic state 58 is the central piece of information used by diagnostic state machine 56 in deriving VMV 26, VU 28, MV status 30, and device status 32. Because diagnostic state 58 may itself be helpful to users performing maintenance on sensor 12, it is the basis of diagnostic information 34, which is output upon a request by data control and management system 16.

Referring also to Fig. 6, transmitter 24 performs the following operations during each sampling period. After getting raw data 44 from transducer 22 (step 72), diagnostic state machine 56 propagates raw data 44 through a set of device equations 60 to generate RMV 36 (step 74). At the same time, transmitter 24 dynamically calculates RU 62 using an uncertainty analysis 64 based on device equations 60 and calibration data 66 in accordance with the established standards discussed above (step 74). In calculating RU 62, transmitter 24 assumes that no fault has occurred. RU 62 has a non-zero value under all operating conditions. Generally, RU 62 increases under other than ideal conditions.

Next, diagnostic state machine 56 obtains other information (step 76) and, based on the other information, raw data 44, RMV 36, and RU 62, calculates statistics or performs pattern matching to determine if

sensor 12 is operating correctly (step 78). Based on the results of step 78, diagnostic state machine 56 updates diagnostic state 58 (step 80).

Next, diagnostic state machine 56 modifies (68) RMV 36 based on diagnostic state 58 to produce VMV 26. Essentially, diagnostic state machine 56 recalculates RMV 36 after modifying the parameters used in the calculation to account for diagnostic state 58 and sets VMV 26 equal to the new RMV 36 (step 82). Thus, under normal operating conditions (when diagnostic state 58 does not require modification of any parameters), VMV 26 typically equals RMV 36.

At the same time, diagnostic state machine 56 modifies (70) RU 62 based on diagnostic state 58 to produce VU 28. As with VMV 26, diagnostic state machine 56 recalculates RU 62 after modifying the parameters used in the calculation to account for diagnostic state 58 and sets VU 28 equal to the new RU 62 (step 82). Thus, VU 28 typically equals RU 62 under normal operating conditions. Under other conditions, VU 28 typically exceeds RU 62.

Next, diagnostic state machine 56 selects MV status 30 (step 84) and device status 32 (step 86) based on diagnostic state 58 and via either calculations or a lookup table. If necessary, diagnostic state machine 56 sends alarm data 35 by updating alarm flags (step 88). Also, if data control and management system 16 has requested it, diagnostic state machine 56 generates diagnostic information 34 based on diagnostic state 58 (step 90).

Referring to Fig. 7, a self-validating temperature sensor 100 includes a thermocouple 102 and a transmitter 104 that includes a processor 106. Typically, thermocouple 102 includes two dissimilar metals in contact and produces a voltage, V_{Diff}, between two terminals 108 and 110. V_{Diff} is proportional to the

difference between the temperature of a sensing junction 112 and a reference junction 114. The sum of V_{Diff} and V_{Comp}, a voltage proportional to the difference between the temperature of reference junction 114 and zero degrees, equals V_{Temp}, a voltage proportional to the difference between the temperature of sensing junction 112 and zero degrees. To determine V_{temp}, V_{diff} is amplified by amplifier 116 and V_{comp} is generated by temperature sensor 118 and amplified by amplifier 120. The output 117 of amplifier 116 and the output 121 of amplifier 120 are then supplied to an analog-to-digital convertor ("ADC") 122 in processor 106. Processor 106 uses amplifier outputs 117, 121, and other available information, to generate diagnostic state 58, RMV 36, and RU 62. Based on these signals, processor 106 generates VMV 26, VU 28, MV status 30, device status 32, alarm data 35, and, when requested, diagnostic information 34.

Referring to Fig. 8, self-validating temperature sensor 100 responds to a loss of power to amplifiers 116, 120 as described below. During normal operation (time 0 to 15), VMV 26 equals RMV 36, which processor 106 generates based on the sum of outputs 117, 121. Similarly, VU 28 equals RU 62, and indicates the uncertainty of VMV 26. MV status 30 is CLEAR.

At time 15, the power supply 132 stops functioning and V_{Diff} and V_{Comp} (outputs 117, 121) both go to zero volts, which results in an RMV 36 of about negative 55°C (for a particular transmitter design). Processor 106 detects the loss of power when power monitor 134, a digital auxiliary signal, switches from one to zero in response to the loss of power. Processor 106 then sets diagnostic state 58 to indicate that processor 106 has zero confidence in RMV 36. As a result, processor 106 sets VMV 26 and VU 28 to a combination of the long and short term past values for VMV 26 and VU 28 respectively

as described above. Finally, processor 106 signals the severity and expected long term duration of the sensor fault by setting MV status 30 to BLIND.

When the power supply is restored at time 36, processor 106 detects the change in power monitor 134 from zero to one and sets MV status 30 to BLURRED. The "live" data from RMV 36 is merged with the previous value of VMV 26 as described above to give a new value for VMV 26. Similarly, RU 62 is merged with the previous value of VU 28 to give a decreasing value for VU 28. At this time, processor 106 also initializes a recovery timer.

Processor 106 generates VMV 26 and VU 28 by merging past values of VMV 26 and VU 28 with, respectively, RMV 36 and RU 62 until the recovery timer expires at time 56. (In this example, the recovery timer was set for 20 seconds.) At that time, processor 106 sets MV status to CLEAR, sets VMV 26 equal to RMV 36, and sets VU 28 equal to RU 62.

Referring now to Fig. 9, an open circuit fault occurs at time 13 when thermocouple 102 is disconnected from transmitter 104. In the presence of such a fault, RMV 36 is around 130°C, which corresponds to a normal value for output 121 but an abnormally high value for output 117 due to saturation of amplifier 116. (Pull-up resistor 136 causes saturation of amplifier 116 in the presence of an open circuit fault.) In response to the abnormally high value of output 117, processor 106 sets diagnostic state 58 to indicate zero confidence in RMV 36 and sets MV status 30 to DAZZLED. Processor 106 then generates VMV 26 and VU 28 based on a combination of the long and short term past values as described above.

Next, referring again to Fig. 7, processor 106 connects thermocouple 102 to voltage source 124 via switch 126 and monitors the voltage 130 produced across a resistor 128. Because of the open circuit, no current

flows in resistor 128 and voltage 130 is zero volts. From this, processor 106 confirms the open circuit fault and sets MV status 30 to BLIND.

At time 27, the open circuit fault is corrected and output 117 returns to a normal value. Processor 106 responds by setting diagnostic state 58 to indicate reduced confidence in RMV 36 (rather than no confidence), sets MV status 30 to BLURRED, and initializes a recovery timer.

Thereafter, processor 106 generates VMV 26 and VU 28 by merging past values of VMV 26 and VU 28 with, respectively, RMV 36 and RU 62 until the recovery timer expires at time 47 (where the recovery timer was set for 20 seconds). At that time, processor 106 sets MV status to CLEAR, sets VMV 26 equal to RMV 36, and sets VU 28 equal to RU 62.

Referring to Fig. 7, a loss of contact fault occurs when sensing junction 112 loses contact with the process element of which the temperature is being measured. Because a loss of contact fault does not produce an abnormal change in RMV 36, sensor 100 cannot readily detect the fault.

As a result, sensor 100 uses current injection tests to detect loss of contact faults. In a current injection test, sensor 100 connects thermocouple 102 to voltage source 124 for a predetermined period and measures the effect on output 117. (The value of output 117 before thermocouple 102 is connected to voltage source 124 is compared to the value after disconnection.)

Referring to Fig. 10, a loss of contact fault occurs at time 12 and the measured temperature drops by about seven degrees. Because this is within normal operating parameters, sensor 100 does not immediately recognize the fault, and, instead, adjusts VMV 26 and maintains MV status 30 as CLEAR.

At time 28, processor 106 begins a current injection test. Because amplifier 116 does not read "live" data during the test, processor 106 sets MV status 30 to DAZZLED and generates VMV 26 and VU 28 based on past performance as discussed above. At time 33, processor 106 determines that the fault has occurred and sets MV status 30 to BLURRED. (Processor 106 assumes that, though contact has been lost, the temperature sensed by thermocouple 102 still approximates the actual temperature.)

At time 56, contact is reestablished. However, processor 106 interprets the sudden change in output 117 as a spike and temporarily sets MV status 30 to DAZZLED. When output 117 remains at the increased value, processor 106 sets MV status 30 back to BLURRED. (Processor 106 does not set MV status 30 to CLEAR because processor 106 has not detected the removal of the fault condition.)

At time 66, processor 106 begins another current injection test and sets MV status 30 to DAZZLED. At time 72, processor 106 determines that contact has been reestablished and, in response, sets MV status to BLURRED and initializes a recovery timer. At time 97, the recovery timer (which was set to 25 seconds) expires and processor 106 sets MV status to CLEAR.

Referring to Fig. 11, another example of a self-validating sensor according to the invention is a Coriolis flow meter 150. Flow meter 150 measures three process parameters: mass flow rate, density, and temperature. Mass flow is measured directly using the principle of Coriolis acceleration, without needing to rely on external pressure, temperature, or specific gravity measurements.

Structurally, flow meter 150 consists of a flowtube 152 that is connected to a transmitter 154 by cables 156. Flowtube 152 includes a body 158 to which is

connected an input pipe 160 and an output pipe 162. Two parallel pipe loops 164, 166 extend from body 158. Body 158 contains passages which lead a process fluid from input pipe 160 to the beginning of loop 164, from the end of loop 164 to the beginning of loop 166 and from the end of loop 166 to output pipe 162 (the broken arrows in Fig. 11 show the direction of flow in loops 164, 166).

Transmitter 154 causes loops 164, 166 to pivotally oscillate about their axes of symmetry Y'-Z' and Y-Z by supplying anti-phase sinusoidal signals to electromagnetic drivers 168, 170. Transmitter 154 uses feedback to maintain the signals to drivers 168, 170 at the resonant frequency of loops 164, 166. Transmitter 154 then detects movement of loops 164, 166 via sensors 172, 174, which each produce a voltage that is proportional to the instantaneous velocity between loops 164, 166. Transmitter 154 adjusts the amplitude of the signals to drivers 168, 170 to maintain the average amplitude of the voltages produces by sensors 172, 174 at a constant level.

Transmitter 154 measures mass flow rate, density, and temperature in the following manner. First, transmitter 154 measures the mass flow rate of the process fluid by monitoring the effect of Coriolis forces on loops 164, 166. Coriolis forces acting on sections G'-H' and G-H of oscillating loops 164, 166 cause deflections of loops 164, 166. These deflections result in a phase angle difference between the voltages produced by sensors 172, 174 that is proportional to the mass flow rate. Next, transmitter 154 determines the density of the process fluid from the frequency of oscillation of loops 164, 166 (which equals the frequency of the signals supplied to drivers 168, 170). The density of the process fluid is inversely proportional to the square of the drive frequency. Finally, transmitter 154 measures

the temperature of the process fluid via a temperature sensor 176 located in body 158. Typically, temperature sensor 176 is an RTD device with a resistance that is temperature dependent.

In the context of flow meter 150, the raw data available are the frequency 44c of a signal coming out of temperature sensor 176 (the frequency is proportional to the resistance of temperature sensor 176), frequency 44b of the drive signals applied to drivers 168, 170, and the voltage outputs 44c of sensors 172, 174. From these signals, transmitter 154 derives three RMVs: the temperature of the process fluid 36a, the density of the process fluid 36b, and the mass flow rate 36c (derived from the phase angle between the sensor signals). In addition, transmitter 154 performs uncertainty analyses to produces three RUs (62a, 62b, 62c), each indicating the uncertainty of a corresponding RMV 36.

After generating RMVs 36a-c and RUs 62a-c, transmitter 154 determines the diagnostic state 58 of flow meter 150. This determination is based on raw data 44a-c, RMVs 36a-c, RUs 62a-c, and auxiliary data 46. Based on diagnostic state 58, transmitter 154 adjusts the parameters used in calculating RMVs 36a-c and RUs 62a-c and recalculates these values. Transmitter 154 then outputs the recalculated RMVs 36a-c and RUs 62a-c as VMVs 26a-c and VUs 28a-c. Transmitter 154 also outputs a MV status 30a corresponding to temperature, a MV status 30b corresponding to density, and a MV status 30c corresponding to mass flow rate. Finally, transmitter 154 outputs a single device status 32 corresponding to the status of flow meter 150.

Referring again to Fig. 6, the procedure performed by transmitter 154 during each sample period can be implemented in software. An example of software for implementing of a self-validating Coriolis meter 150 is

included in microfiche appendix 1. In addition, an example of software for implementing a self-validating temperature sensor 100 as described above is included in microfiche appendix 2. The software in appendices 1 and 2 may be implemented on any processor that supports a structured programming language. In an alternative approach, the procedure could be implemented using hard-wired circuitry.

The pseudocode shown in Fig. 12 provides a simplified view of the procedure performed by transmitter 154 during each sample period. Fig. 12 also shows, in parentheses, the steps performed in Fig. 6 that correspond to the steps in Fig. 12. Initially, transmitter 154 gets raw data 44a-c from flowtube 152 (step 200). Transmitter 154 then calculates RMVs 36a-c and RUs 62a-c (steps 202-206). The pseudocode for calculating RMV 36a and RU 62a is shown in Fig. 13 and is discussed below. Next, transmitter 154 examines all available information (step 208) and determines diagnostic state 58, MV statuses 30a-c, and device status 32 (step 210). A portion of the pseudocode for determining diagnostic state 58 and MV statuses 30a-c is shown in Fig. 14 and discussed below. Based on diagnostic state 58, transmitter 154 corrects the parameters used in calculating RMV 36a-c and RU 62a-c (step 212). Transmitter 154 then calculates VMVs 26a-c and VUs 28a-c (steps 214-218) using the procedure with which RMVs 36a-c and RUs 62a-c were calculated and corrected parameters.

Referring to Fig. 13, transmitter 154 calculates RMV 36a and RU 62a as follows. First, transmitter 154 calculates the resistance "R" of temperature sensor 176 (step 250). Transmitter 154 then calculates the uncertainty "d_R" of R based on an uncertainty analysis of the equation used to calculate R (step 252). Next,

transmitter 154 calculates "temperature" (step 254), and sets RMV 36a equal to temperature. Finally, transmitter 154 calculates the uncertainty "d_temperature" of temperature (step 256), and sets RU 62a equal to d_temperature. Thus, as a first pass RMV 36a and RU 62a equal the measured temperature and its corresponding uncertainty. If transmitter 154 subsequently determines that it has less than nominal confidence in RMV 36a and RU 62a, transmitter 154 modifies any of the parameters, uncertainties, and/or raw data (e.g., RK1, d_RK1, f_RTD) used in calculating temperature and d_temperature to reflect the impact of an expected fault. Transmitter 154 then reperforms the procedure illustrated in Fig. 13 using the modified information and sets VMV 26a and VU 28a equal to the new values for temperature and d_temperature. Alternatively, if transmitter 154 determines that the fault is too severe, transmitter 154 may set VMV 26a and VU 28a based on historical data.

Fig. 14 illustrates the procedure used by transmitter 154 to detect and respond to a loss of input from temperature sensor 176. Transmitter 154 maintains a variable, RTD_input_state, that indicates the current status of the input from temperature sensor 176. As a first step, transmitter 154 checks RTD_input state (step 300).

If RTD_input_state equals RTD_INPUT_OK, which indicates that the input from temperature sensor 176 was functioning normally during the previous sample period, transmitter 154 checks the resistance of temperature sensor 176 (step 304). If the resistance is less than 80 ohms, this indicates that the connection between transmitter 154 and temperature sensor 176 has been lost. In response, transmitter 154 sets RTD_input_state to RTD_INPUT_LOST (step 306). Transmitter 154 then checks the value of RTD_spike_state, which indicates whether

transmitter 154 had sensed a spike in the output from temperature sensor 176 during the previous sample (step 308). If RTD_spike_state indicates that a spike had occurred, transmitter 154 resets RTD_input_state to indicate no spike (step 310). (A spike is a less serious fault and is mooted by the loss of connection.)

If RTD_input_state equals RTD_INPUT_LOST, transmitter 154 checks the resistance of temperature sensor 176 (step 314). If the resistance is less than 100 ohms (step 314), this indicates that connection with temperature sensor 176 is still lost. (Different resistance values are used in steps 304 and 314 to avoid intermittent switching of RTD_input_state if, for example, the resistance fluctuates between 79 and 81 ohms.) If connection is lost, transmitter 154 sets MV status 30a, which corresponds to temperature, to BLIND (step 316) and substitutes historical information (step 318) about temperature for use in the recalculation steps (steps 214-18 of Fig. 12). Because density and mass flow are based, in part, on temperature, transmitter 154 sets MV statuses 30b-c to BLURRED (steps 320-22). If the resistance is greater than 100 ohms, transmitter 154 sets RTD_input state to RTD_INPUT_RECOVER, to indicate that connection has been reestablished (step 326). At this time, transmitter 154 initializes a recovery timer by setting RTD_input_count equal to zero (step 328).

If RTD_input_state equals RTD_INPUT_RECOVER, transmitter 154 merges the past and present values for temperature as discussed above (step 332). Transmitter 154 then checks to see if the recovery timeout period has expired (step 334). If it has, transmitter 154 sets RTD_input_state to RTD_INPUT_OK (step 336). If it has not, transmitter 154 sets MV status 30a to BLURRED (step 340) and increments RTD_input_count (step 342).

Fig. 15 illustrates the response of flow meter 150 to a loss of input from temperature sensor 176. At time 9, the loss of input occurs and the unvalidated temperature measurement, RMV 36a, begins to rapidly drop. At time 10, transmitter 154 sets diagnostic state 58 to indicate that a spike in the temperature input has occurred, and, in response, changes MV status 30a to DAZZLED, modifies VMV 26a and VU 28a based on past performance as discussed above, and leaves MV statuses 30b-c, VMVs 26b-c, and VUs 28b-c unchanged (though, because density and mass flow rate are partially dependent on temperature, VMVs 26b-c and VUs 28b-c include the changes to VMV 26a and VU 28a).

At time 12, the resistance of temperature sensor 176 drops sufficiently low that transmitter 154 sets diagnostic state 58 to indicate that a loss of temperature input has occurred, and, in response, changes MV status 30a to BLIND, continues to base VMV 26a and VU 28a on past performance, changes MV statuses 30b-c to BLURRED, and leaves VMVs 26b-c unchanged. Because the uncertainties of density and mass flow are based in part on the uncertainty of temperature, VUs 28b-c will increase to reflect the increase in VU 28a.

At time 48, the resistance of temperature sensor 176 increases to a sufficient level so that transmitter 154 sets diagnostic state 58 to indicates that temperature input has been recovered, and, in response, changes MV status 30a to BLURRED, initializes a recovery timer, begins merging past and present values for VMV 26a and VU 28a, and changes MV statuses 30b-c to CLEAR.

At time 72, the recovery timer expires, and transmitter 154 sets diagnostic state 58 to indicate that the temperature input is fully recovered, and, in response, changes MV status 30a to CLEAR and bases VMV 26a and VU 28a on RMV 36a and RU 62a.

Other embodiments are within the following claims.

What is claimed is:

Claims

1. A sensor for providing a measurement and information about the validity of the measurement, said sensor comprising:

a transducer for generating a data signal related to the value of a variable and

a transmitter for receiving said data signal and generating in response thereto a first output signal indicating a measurement of said variable and a second output signal based on a dynamic uncertainty analysis of said first output signal.

2. The sensor of claim 1, wherein, when said sensor experiences a fault, said transmitter modifies said first and second output signals to account for an impact of said fault.

3. The sensor of claim 1, wherein said transmitter generates a third output signal that indicates a state of reliability of said first output signal.

4. The sensor of claim 1, said sensor further comprising a plurality of transducers that generate a plurality of data signals related to the value of one or more variables, wherein said transmitter generates said first output signal based on one or more of said data signals.

5. A sensor for providing measurements and information about the validity of the measurements, said sensor comprising:

one or more transducers for generating a first data signal related to the value of a first variable and

a second data signal related to the value of a second variable,

a transmitter for receiving said first and second data signals and generating in response thereto a first output signal related to a measurement of said first variable, a second output signal based on a dynamic uncertainty analysis of said first output signal, a third output signal related to a measurement of said second variable, and a fourth output signal based on a dynamic uncertainty analysis of said third output signal.

6. The sensor of claim 5, wherein, when said sensor experiences a fault, said transmitter modifies said first, second, third, and fourth output signals to account for an impact of said fault.

7. The sensor of claim 5, wherein said transmitter generates a fifth output signal that indicates a state of reliability of said first output signal.

8. The sensor of claim 7, wherein said transmitter generates a sixth output signal that indicates a state of reliability of said third output signal.

9. The sensor of claim 8, wherein said transmitter generates a seventh output signal that indicates an operational status of said sensor.

10. The sensor of claim 5, wherein said sensor includes a plurality of transducers.

11. The sensor of claim 5, wherein said sensor includes a single transducer.

12. A method of providing a measurement and information about the validity of the measurement comprising the steps of:

receiving a data signal related to the value of a variable;

based on said data signal, estimating a measurement of said variable;

generating a first output signal related to the estimated measurement of said variable;

performing an uncertainty analysis of said first output signal; and

generating a second output signal based on said uncertainty analysis.

13. The method of claim 12, said method further including the step of determining whether said data signal is faulty, wherein, when said data signal is faulty, said estimating step modifies said estimated measurement to account for an impact of said fault.

14. The method of claim 13, wherein, when said data signal is faulty, said uncertainty analysis accounts for an impact of said fault.

15. The method of claim 12, said method further including the step of generating a third output signal that indicates a state of reliability of said first output signal.

16. The method of claim 12, said method further including the step of receiving a plurality of data signals, wherein said estimating step estimates the measurement of said variable based on said plurality of data signals.

17. A method of providing measurements and information about the validity of the measurements comprising the steps of:

receiving a first data signal related to the value of a first variable;

receiving a second data signal related to the value of a second variable;

based on said first data signal, estimating a measurement of said first variable;

generating a first output signal related to the estimated measurement of said first variable;

performing an uncertainty analysis of said first output signal;

generating a second output signal based on said uncertainty analysis of said first output signal;

based on said second data signal, estimating a measurement of said second variable;

generating a third output signal related to the estimated measurement of said second variable;

performing an uncertainty analysis of said third output signal; and

generating a fourth output signal based on said uncertainty analysis of said third output signal.

18. The method of claim 17, said method further including the step of determining whether said first data signal is faulty, wherein, when said first data signal is faulty, said estimating step modifies said estimated measurement of said first variable to account for an impact of said fault.

19. The method of claim 18, wherein, when said first data signal is faulty, said uncertainty analysis of said first output signal accounts for an impact of said fault.

20. The method of claim 17, said method further including the step of determining whether said second data signal is faulty, wherein, when said second data signal is faulty, said estimating step modifies said estimated measurement of said second variable to account for an impact of said fault.

21. The method of claim 20, wherein, when said second data signal is faulty, said uncertainty analysis of said third output signal accounts for an impact of said fault.

22. The method of claim 17, said method further including the step of generating a fifth output signal that indicates a state of reliability of said first output signal.

23. The method of claim 22, said method further including the step of generating a sixth output signal that indicates a state of reliability of said third output signal.

24. A temperature sensor for providing a temperature measurement and information about the validity of the temperature measurement, said temperature sensor comprising:

a transducer for generating a data signal related to a temperature and

a transmitter for receiving said data signal and generating in response thereto said temperature measurement and an uncertainty signal based on a dynamic uncertainty analysis of said temperature measurement.

25. The sensor of claim 24 wherein, when said temperature sensor experiences a fault, said transmitter

modifies said temperature measurement and said uncertainty signal to account for an impact of said fault.

26. The sensor of claim 24, wherein said transmitter generates a third output signal that indicates a state of reliability of said temperature measurement.

27. A Coriolis flow meter for providing measurements of mass flow, density, and temperature and information about the validity of the measurements, said Coriolis flow meter comprising:

one or more transducers for generating a first data signal related to mass flow, a second data signal related to density, and a third data signal related to temperature,

a transmitter for receiving said first, second, and third data signals and generating in response thereto a mass flow measurement signal, a first uncertainty signal based on a dynamic uncertainty analysis of said mass flow measurement signal, a density measurement signal, a second uncertainty signal based on a dynamic uncertainty analysis of said density measurement signal, a temperature measurement signal, and a third uncertainty signal based on a dynamic uncertainty analysis of said temperature measurement signal.

28. The Coriolis flow meter of claim 27, wherein, when said Coriolis flow meter experiences a fault, said transmitter modifies said measurement signals and said uncertainty signals to account for an impact of said fault.

29. The Coriolis flow meter of claim 27, wherein said transmitter generates a first reliability signal that indicates a state of reliability of said mass flow measurement signal, a second reliability signal that indicates a state of reliability of said density measurement signal, and a third reliability signal that indicates a state of reliability of said temperature measurement signal.

30. The Coriolis flow meter of claim 29, wherein said transmitter generates a operational status signal that indicates an operational status of said Coriolis flow meter.

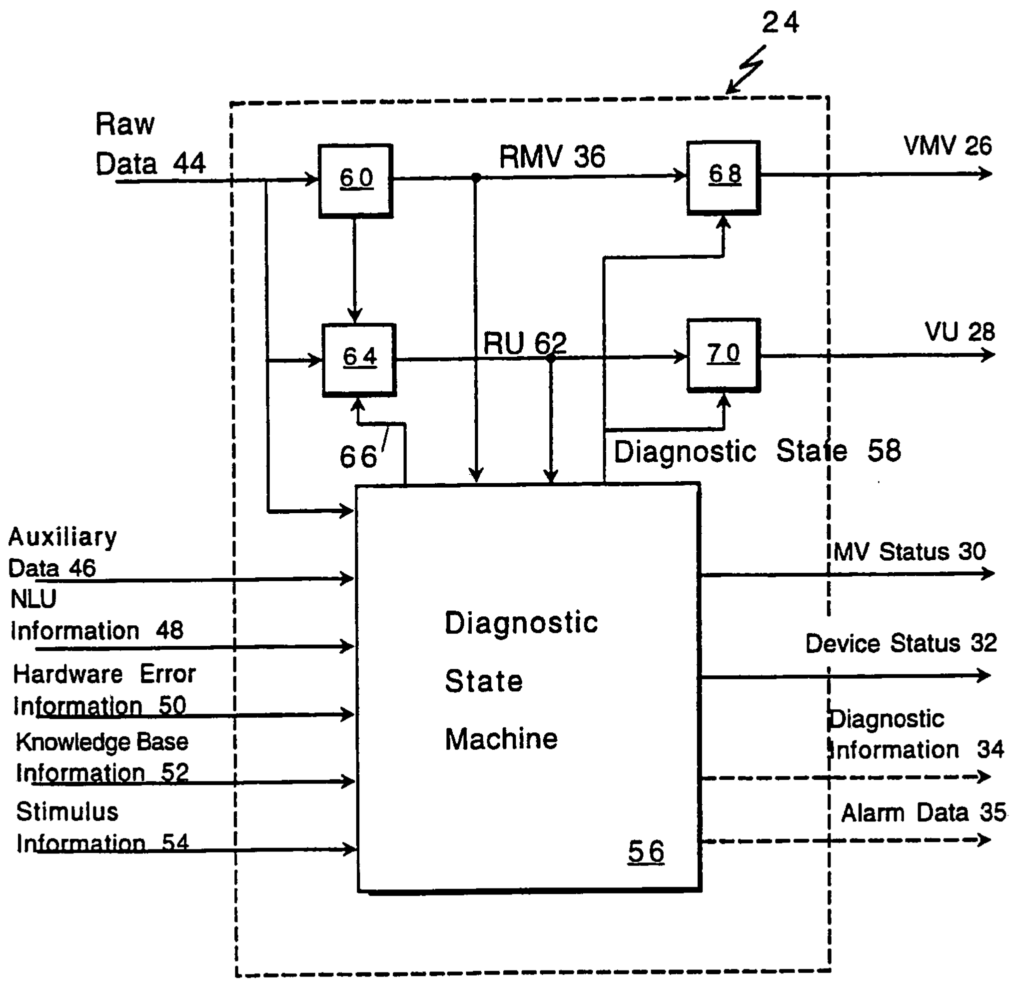

24
Raw
Data 44
60
RMV 36
68
VMV 26
64
RU 62
70
VU 28
66
Diagnostic State 58
Auxiliary
Data 46
NLU
Information 48
Hardware Error
Information 50
Knowledge Base
Information 52
Stimulus
Information 54
Diagnostic
State
Machine
56
MV Status 30
Device Status 32
Diagnostic
Information 34
Alarm Data 35

FIG. 3

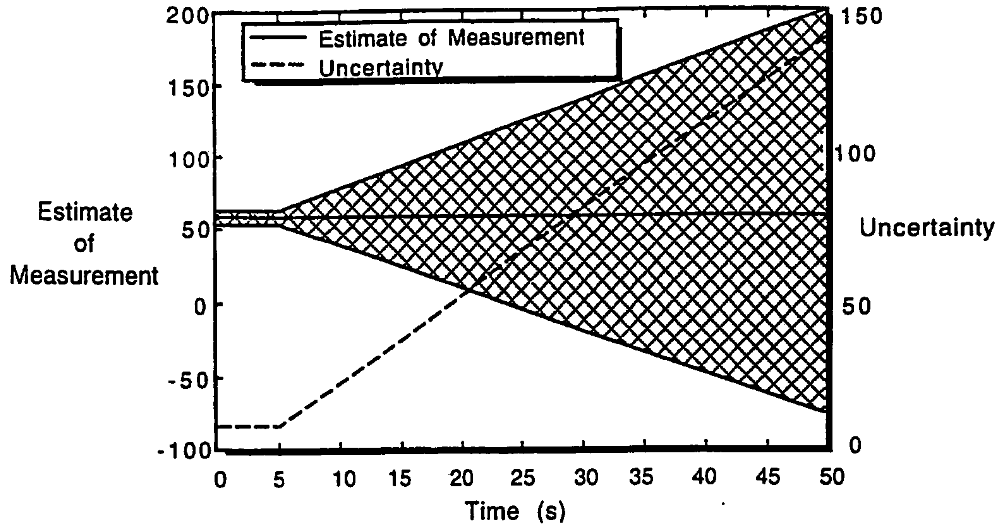


FIG. 4a

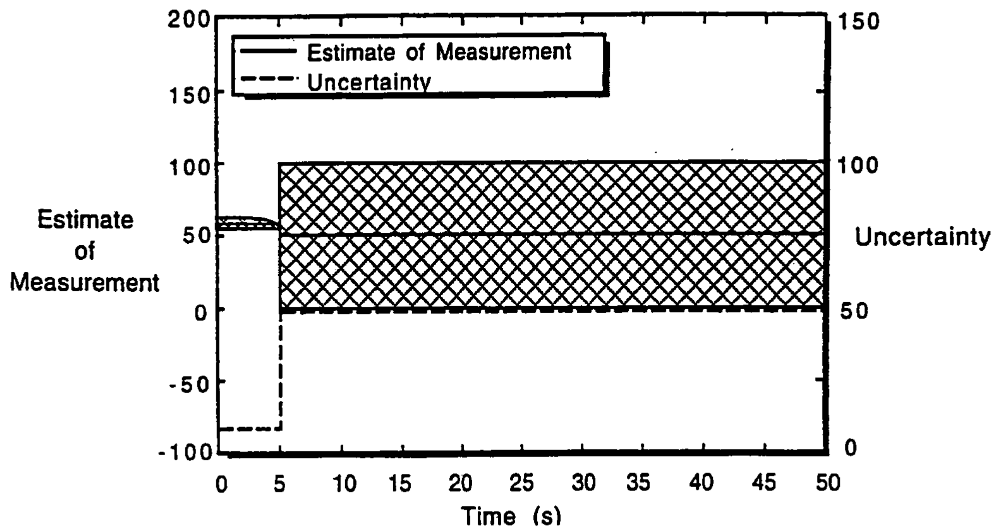


FIG. 4b

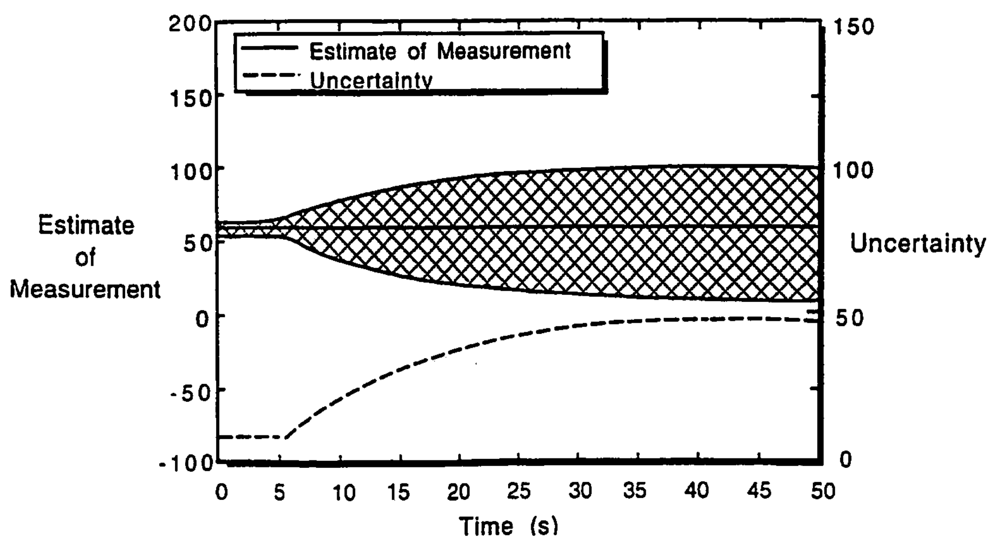


FIG. 4c

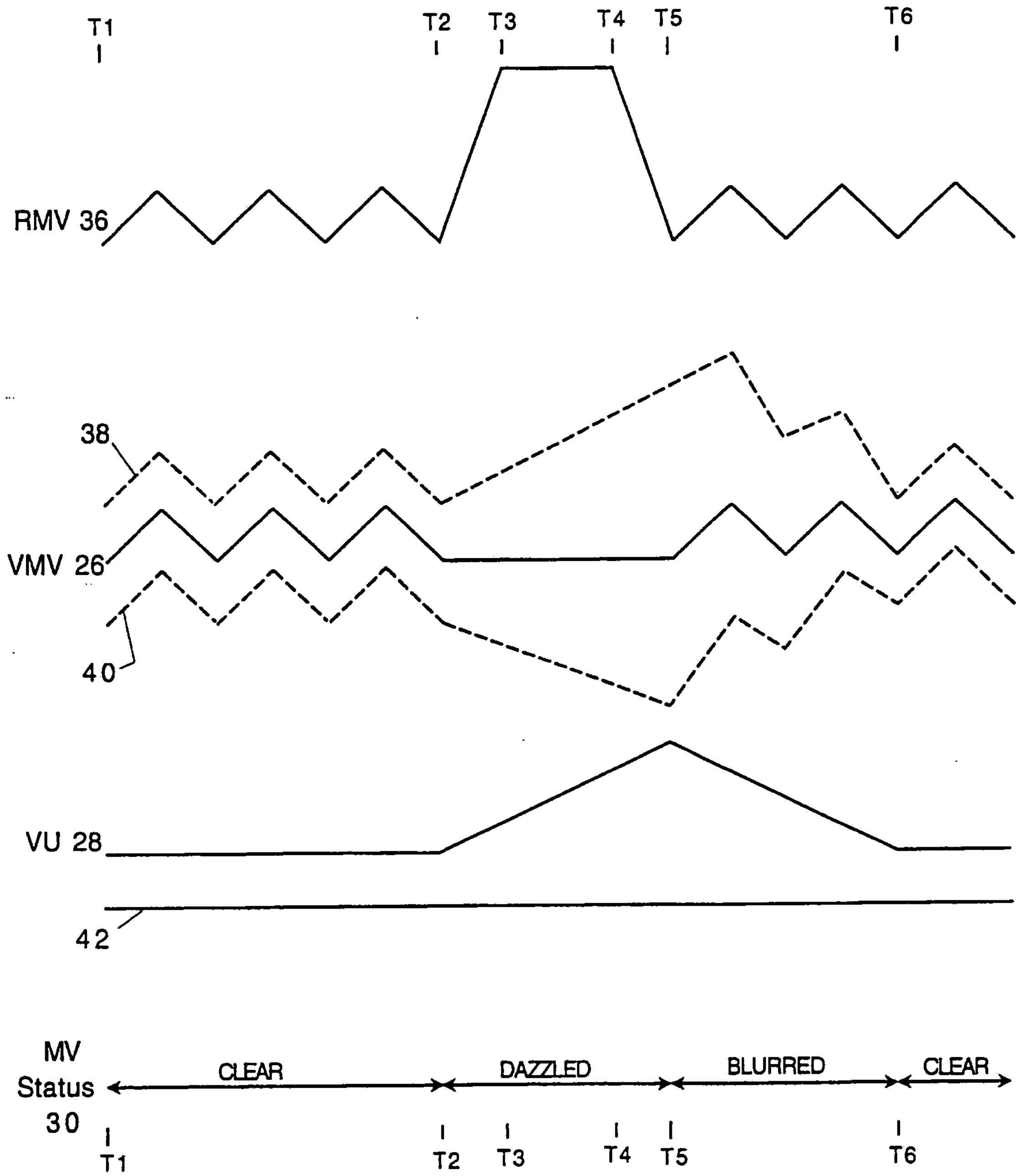

T1
T2
T3
T4
T5
T6
RMV 36
38
VMV 26
40
VU 28
42
MV Status 30
CLEAR
DAZZLED
BLURRED
CLEAR
T1
T2
T3
T4
T5
T6

FIG. 5

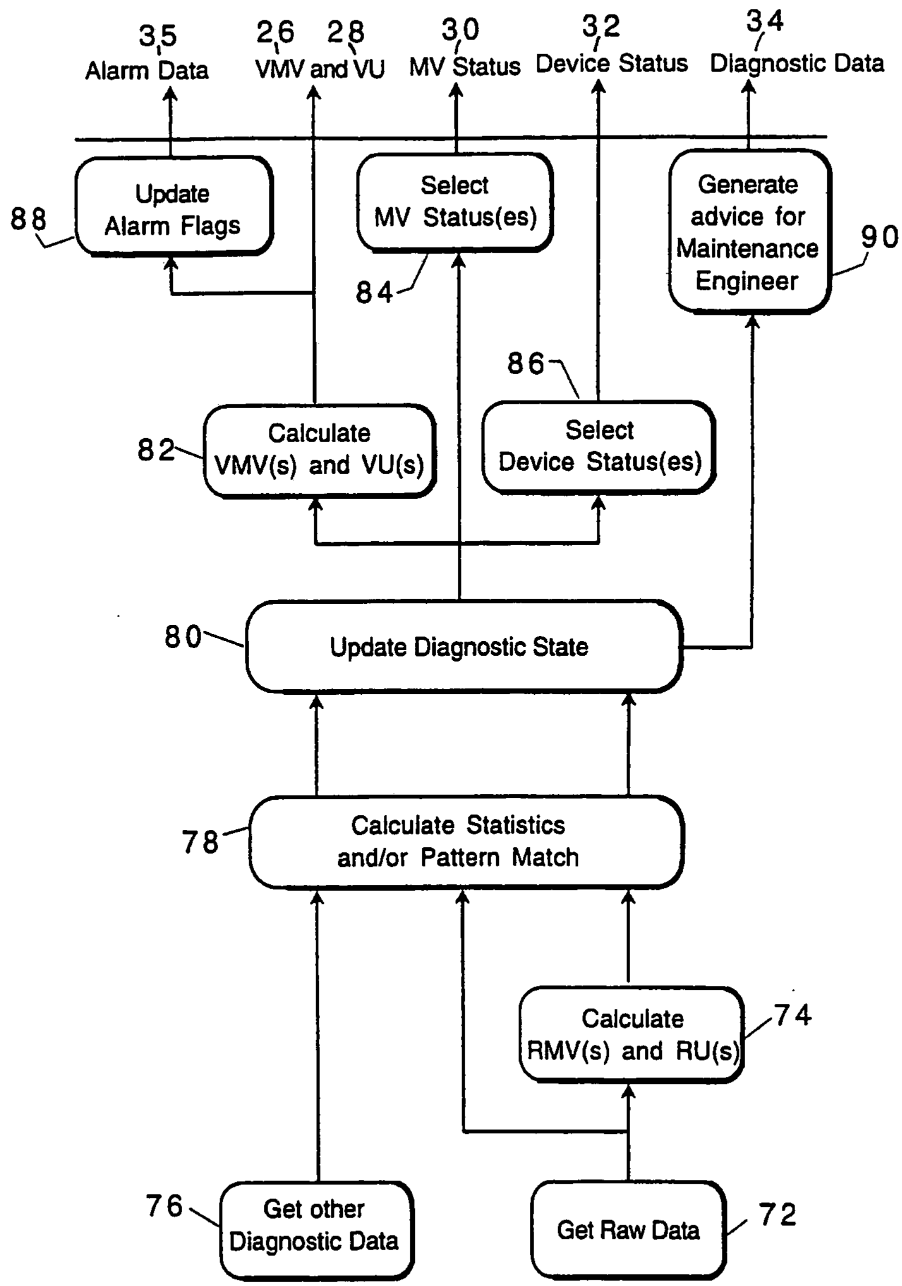

35
Alarm Data
26
28
VMV and VU
30
MV Status
32
Device Status
34
Diagnostic Data
Update Alarm Flags
88
Select MV Status(es)
84
Generate advice for Maintenance Engineer
90
86
Calculate VMV(s) and VU(s)
82
Select Device Status(es)
80
Update Diagnostic State
78
Calculate Statistics and/or Pattern Match
Calculate RMV(s) and RU(s)
74
76
Get other Diagnostic Data
Get Raw Data
72

FIG. 6

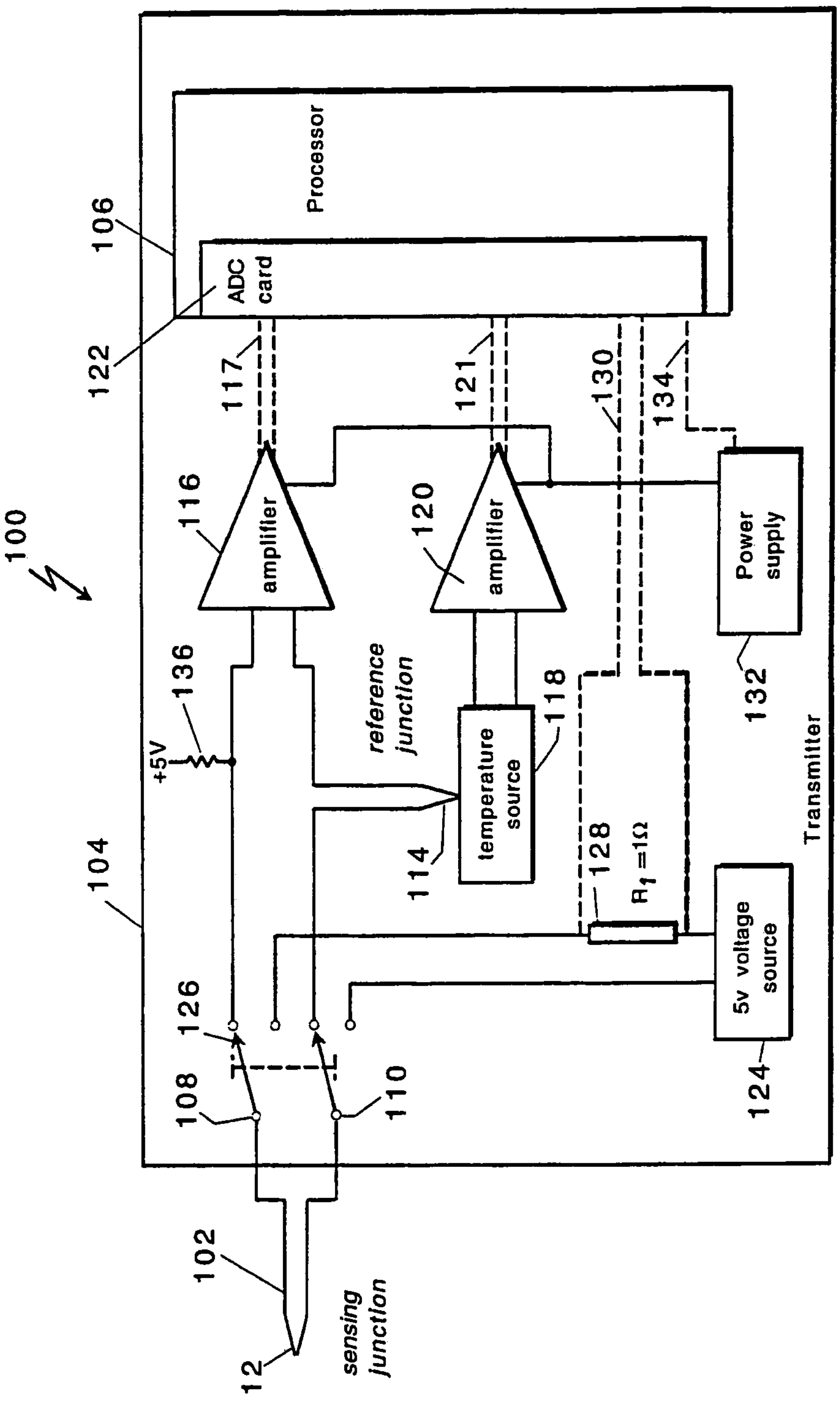
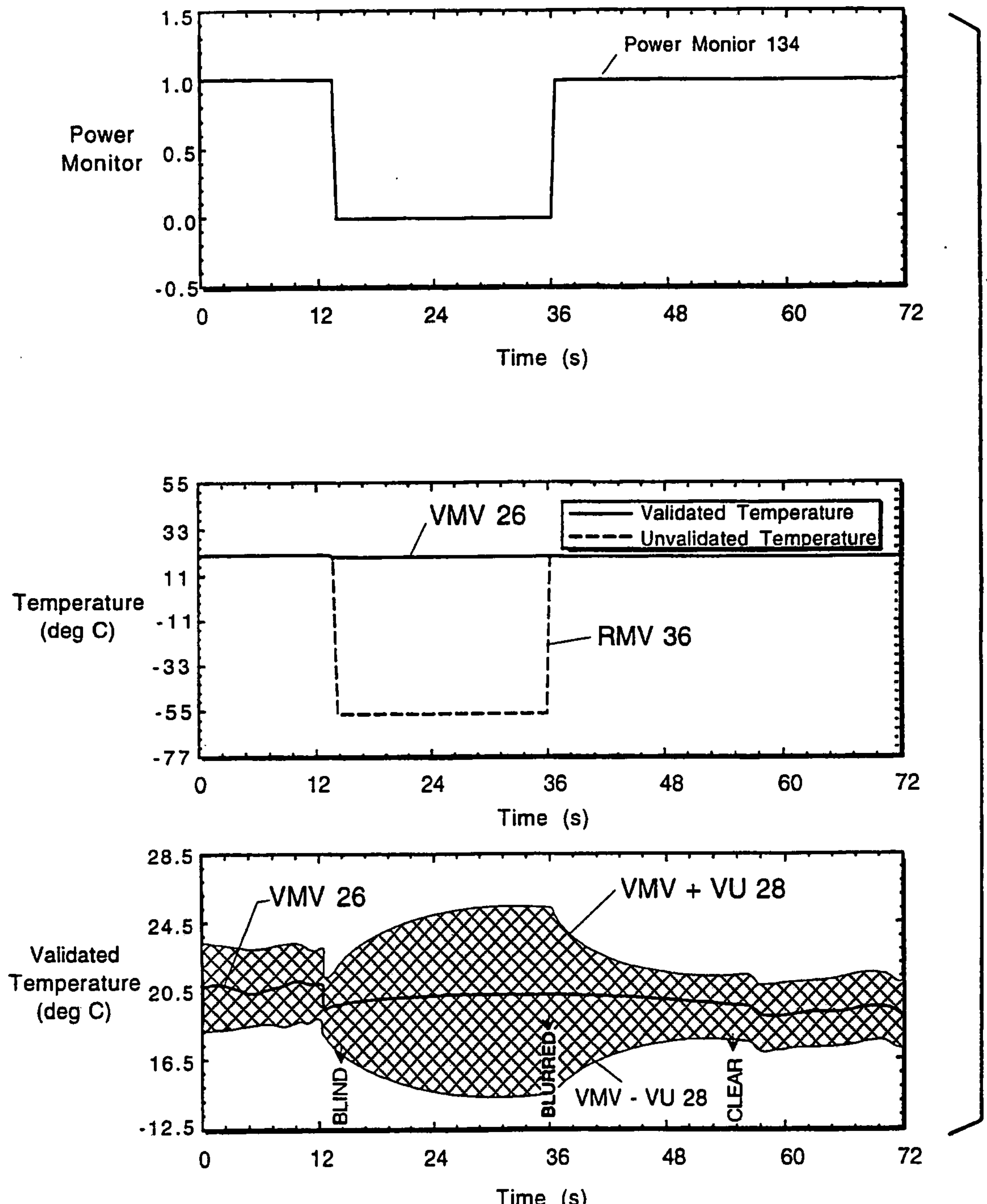

100
Processor
ADC card
106
122
117
121
130
134
116
amplifier
120
amplifier
Power supply
132
136
+5V
reference junction
temperature source
118
114
128
R1 =1Ω
Transmitter
104
5v voltage source
124
126
108
110
102
112
sensing junction

FIG. 7



1.5
1.0
0.5
0.0
-0.5
Power Monitor
Power Monior 134
0
12
24
36
48
60
72
Time (s)
55
33
11
-11
-33
-55
-77
Temperature (deg C)
VMV 26
Validated Temperature
Unvalidated Temperature
RMV 36
Time (s)
28.5
24.5
20.5
16.5
-12.5
Validated Temperature (deg C)
VMV 26
VMV + VU 28
BLIND
BLURRED
VMV - VU 28
CLEAR
Time (s)

FIG. 8

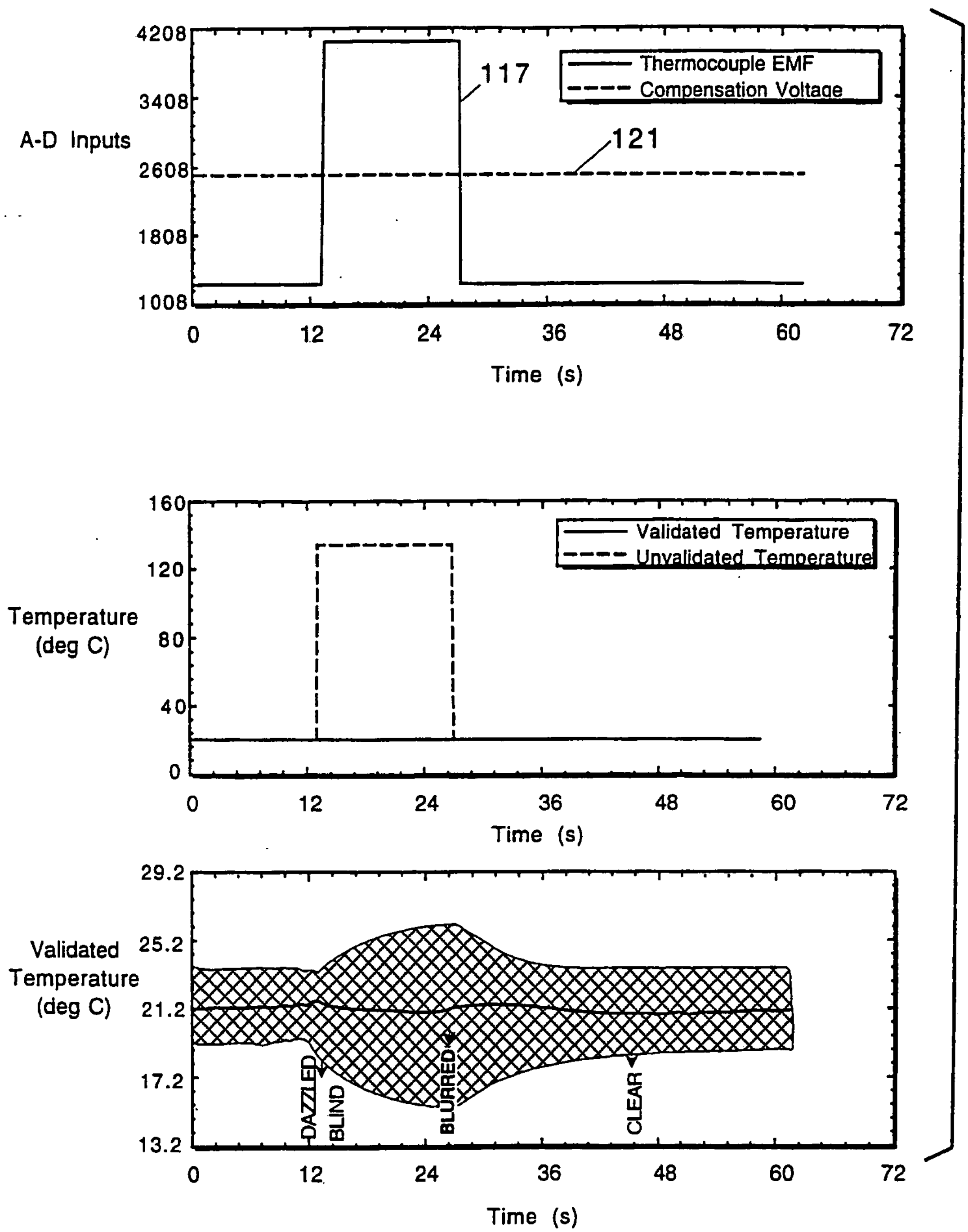

4208
3408
A-D Inputs
2608
1808
1008
Thermocouple EMF
Compensation Voltage
117
121
0
12
24
36
48
60
72
Time (s)
160
120
Temperature
(deg C)
80
40
0
Validated Temperature
Unvalidated Temperature
0
12
24
36
48
60
72
Time (s)
29.2
Validated
Temperature
(deg C)
25.2
21.2
17.2
13.2
DAZZLED
BLIND
BLURRED
CLEAR
0
12
24
36
48
60
72
Time (s)

FIG. 9

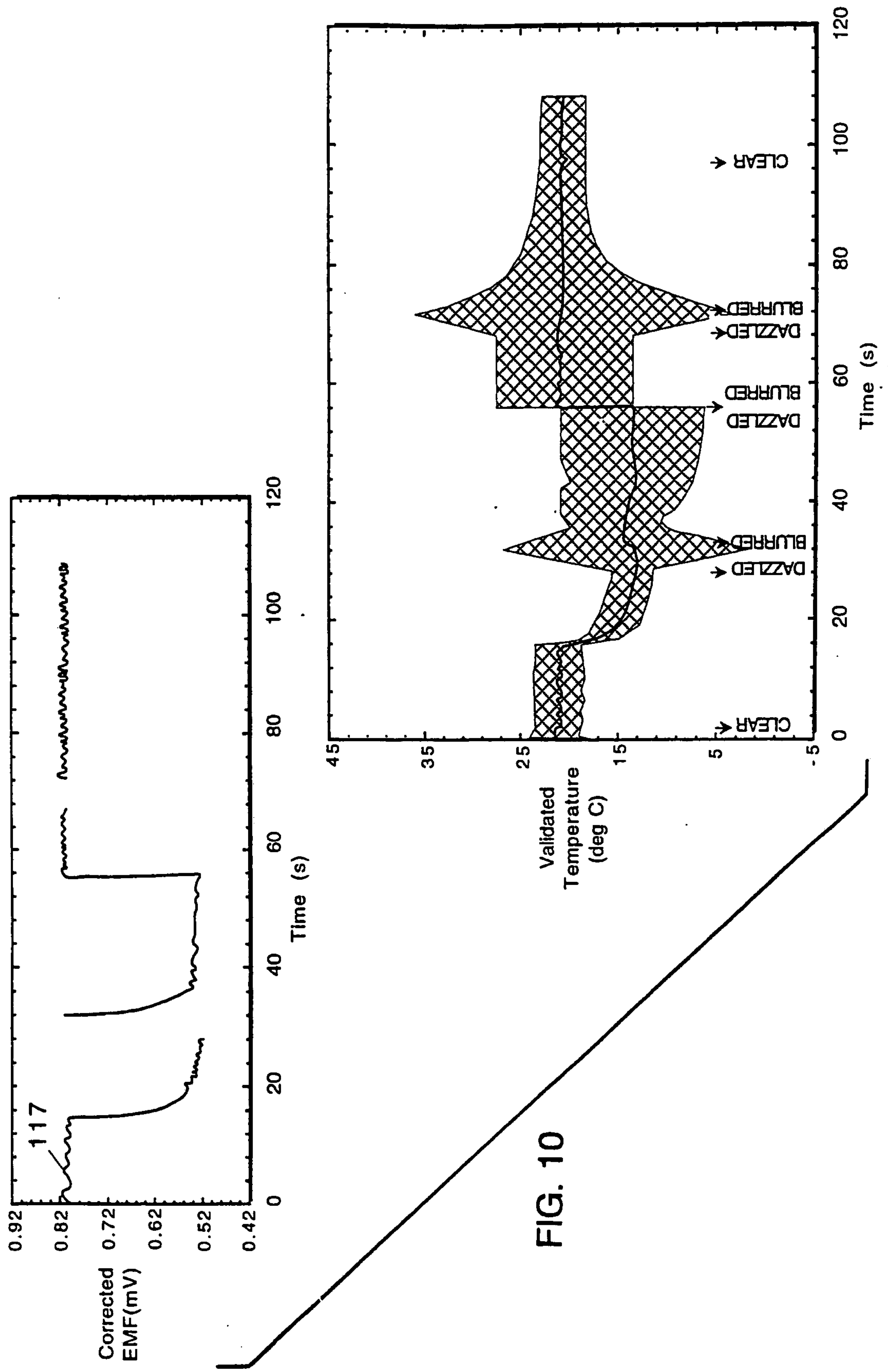

Corrected EMF(mV)
0.92 0.82 0.72 0.62 0.52 0.42
117
0 20 40 60 80 100 120
Time (s)
Validated Temperature (deg C)
45 35 25 15 5 -5
CLEAR
DAZZLED
BLURRED
DAZZLED
BLURRED
DAZZLED
BLURRED
CLEAR
0 20 40 60 80 100 120
Time (s)

FIG. 10

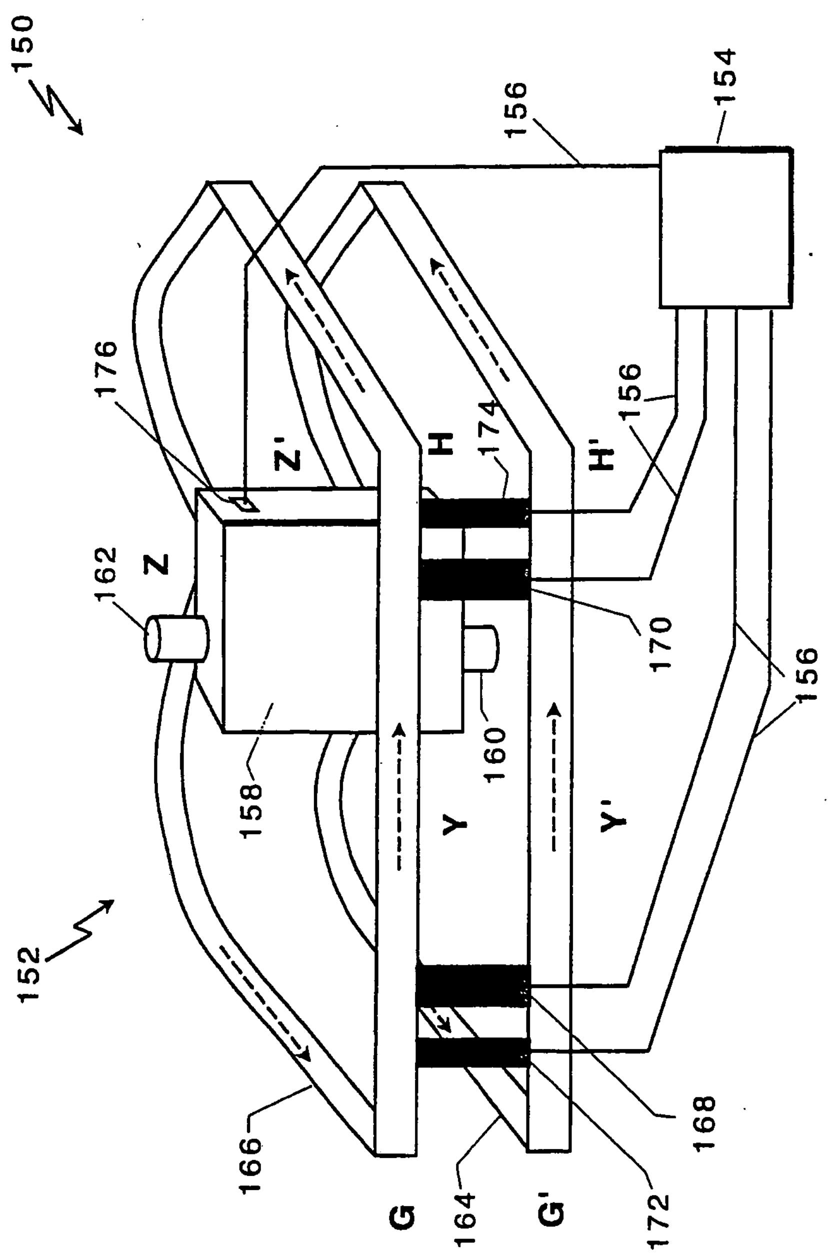

150
152
154
156
156
156
156
158
160
162
164
166
168
170
172
174
176
Z
Z'
H
H'
Y
Y'
G
G'

FIG. 11

Step/ (Fig. 6 step)	Action
200 (72)	Get raw data.
202 (74)	Calculate temperature RMV and RU.
204 (74)	Calculate density RMV and RU.
206 (74)	Calculate mass flow RMV and RU.
208 (74)	Consider all inputs.
210 (78, 80, 84, 86)	Make diagnosis.
212 (80)	Correct all inputs.
214 (82)	Calculate temperature VMV and VU.
216 (82)	Calculate density VMV and VU.
218 (82)	Calculate mass flow VMV and VU.

FIG. 12

Step	Action
250	R = (RK1 * tran_temp + RK2) * f_RTD + RK3 * tran_temp + RK4 [RK1-4 are calibration constants, tran_temp is the temperature of transmitter 154, and f_RTD is the frequency of the signal coming out of RTD temperature sensor 176.]
252	d_R = sqrt (sqr (tran_temp * f_RTD * d_RK1) + sqr (f_RTD * d_RK2) + sqr (tran_temp * d_RK3) + sqr (d_RK4) + sqr ((RK1 * f_RTD + RK3) * d_tran_temp) + sqr ((RK1 * tran_temp + RK2) * d_f_RTD)) [d_x is the uncertainty of x.]
254	temperature = RTD_A * R * R + RTD_B * R + RTD_C
256	d_temperature = (2.0 * RTD_A * R + RTD_B) * d_R

FIG. 13

```
Step    Action

300     Check RTD_ input_state
302         If RTD_INPUT_OK
304             If RTD_ resistance < 80.0
306                 RTD_input_state = RTD_INPUT_LOST
308                 If RTD_spike_state <> RTD_SPIKE_OFF
310                     RTD_spike_state = RTD_SPIKE_OFF

312         If RTD_INPUT_LOST
314             If RTD_ resistance < 100.0
316                 Temperature MV status = BLIND
318                 Substitute historical temperature
320                 Density MV status = BLURRED
322                 Mass Flow MV status = BLURRED
324             Else
326                 RTD_input_state = RTD_INPUT_RECOVER
328                 RTD_input_count = 0

330         If RTD_INPUT_RECOVER
332             Merge past and present temperature
334             If RTD_input_count = 90
336                 RTD_input_state = RTD_INPUT_OK
338             Else
340                 Temperature MV status = BLURRED
342                 Increment RTD_input_count
```

FIG. 14

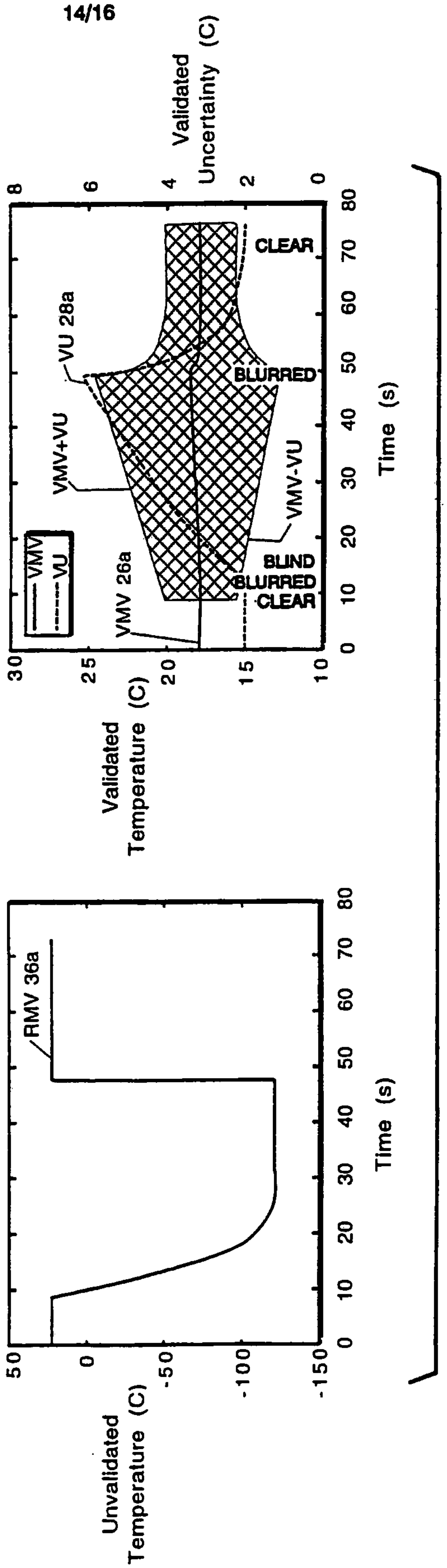

Validated Uncertainty (C)
Validated Temperature (C)
VMV
VU
VU 28a
VMV+VU
VMV-VU
VMV 26a
CLEAR
BLURRED
BLIND
BLURRED
CLEAR
Time (s)
Unvalidated Temperature (C)
RMV 36a
Time (s)

FIG. 15a

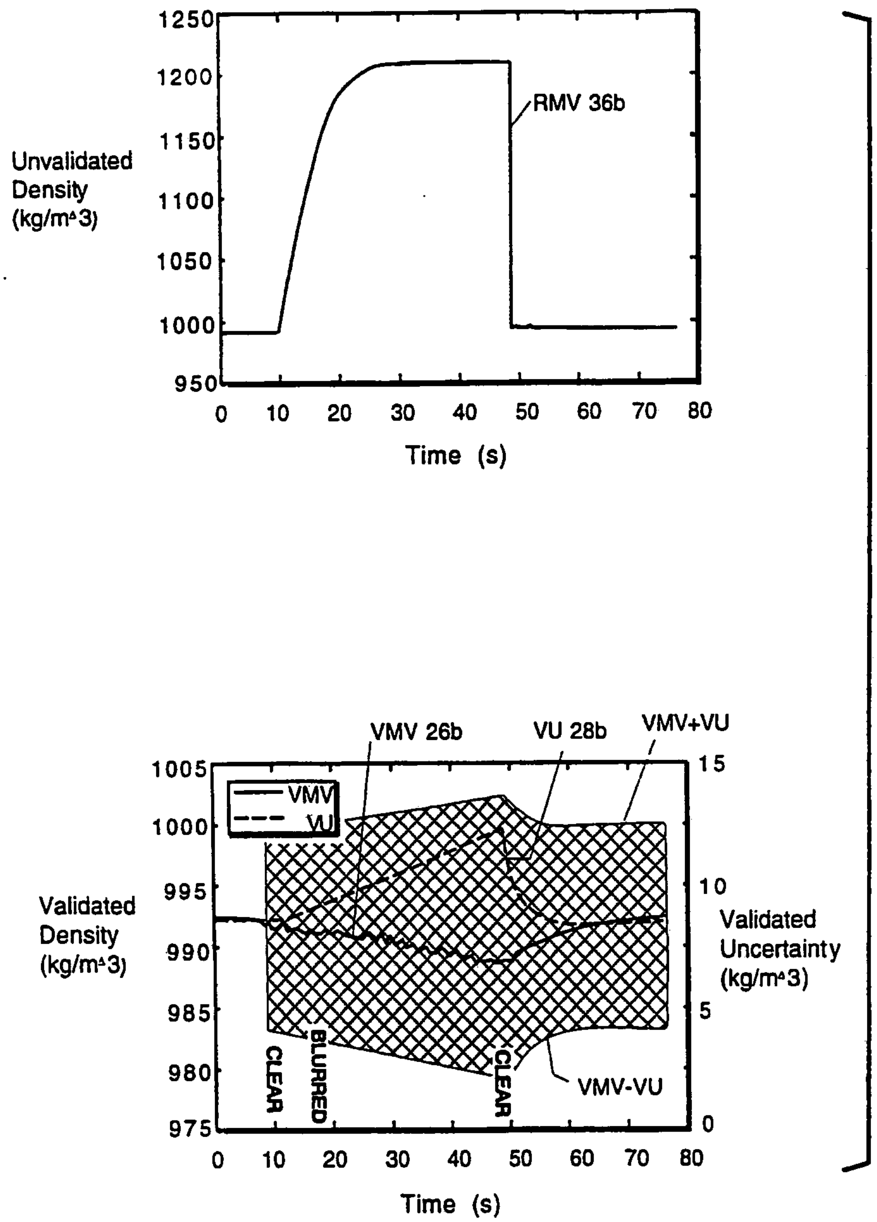

Unvalidated Density (kg/m^3)
1250
1200
1150
1100
1050
1000
950
RMV 36b
0 10 20 30 40 50 60 70 80
Time (s)
VMV 26b
VU 28b
VMV+VU
VMV
VU
Validated Density (kg/m^3)
1005
1000
995
990
985
980
975
15
10
5
0
Validated Uncertainty (kg/m^3)
CLEAR
BLURRED
CLEAR
VMV-VU
0 10 20 30 40 50 60 70 80
Time (s)

FIG. 15b

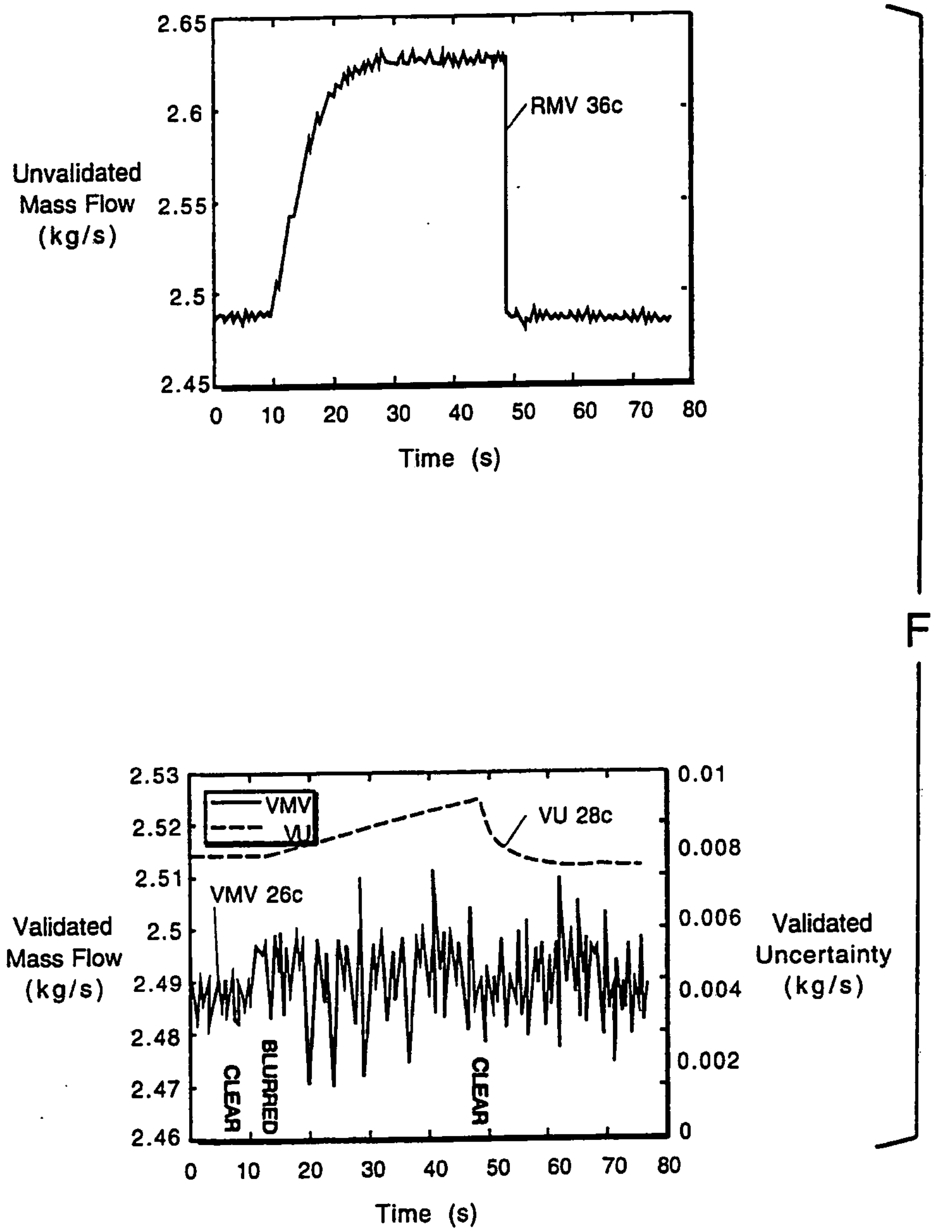

2.65
2.6
2.55
2.5
2.45
Unvalidated
Mass Flow
(kg/s)
RMV 36c
0 10 20 30 40 50 60 70 80
Time (s)
2.53
2.52
2.51
2.5
2.49
2.48
2.47
2.46
Validated
Mass Flow
(kg/s)
VMV
VU
VU 28c
VMV 26c
CLEAR
BLURRED
CLEAR
0.01
0.008
0.006
0.004
0.002
0
Validated
Uncertainty
(kg/s)
0 10 20 30 40 50 60 70 80
Time (s)

FIG. 15c

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 93/03729

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01K15/00; G01F1/84

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01K ; G01F

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	FR,A,2 334 827 (GENERAL ELECTRIC CO) 8 July 1977 see page 3, line 30 - page 5, line 12 see page 7, line 7 - page 11 ---	1-5, 12-17,24
X	COLLOQUIM DIGEST-IEE 11 February 1991, BOSTON pages 1 - 2 M.P. HENRY 'A FAULT-TOLERANT INTERFACE FOR SELF-VALIDATING SENSORS' see the whole document ---	1
X	EP,A,0 413 814 (TERUMO) 27 February 1991 see page 2, line 36 - line 55; figures ---	1,2,12, 13,24
X	US,A,4 934 196 (PAUL ROMANO) 19 June 1990 see abstract; figures --- -/--	1-3, 27-30

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

1

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
07 JULY 1993	21. 07. 93
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	RAMBOER P.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	EP,A,0 122 622 (OMRON TATEISI) 24 October 1984 see abstract ---	1,3,24
A	DE,C,3 540 204 (DAIMLER-BENZ) 25 September 1986 see the whole document -----	24,25

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

US 9303729
SA 73732

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 07/07/93
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
FR-A-2334827	08-07-77	US-A- 4058975	22-11-77
		DE-A- 2655121	23-06-77
		GB-A- 1574835	10-09-80
		JP-A- 52084307	13-07-77
		NL-A- 7613671	10-06-77
EP-A-0413814	27-02-91	JP-A- 63040825	22-02-88
		AU-B- 604745	03-01-91
		AU-A- 7756187	24-02-88
		WO-A- 8801047	11-02-88
US-A-4934196	19-06-90	AU-A- 5812890	07-01-91
		EP-A- 0474743	18-03-92
		JP-T- 4505506	24-09-92
		WO-A- 9015309	13-12-90
		US-A- 4996871	05-03-91
EP-A-0122622	24-10-84	JP-A- 60187830	25-09-85
		JP-A- 60200135	09-10-85
		JP-C- 1724831	24-12-92
		JP-B- 4007457	12-02-92
		JP-A- 59190630	29-10-84
		US-A- 4565456	21-01-86
DE-C-3540204	25-09-86	FR-A- 2590016	15-05-87
		GB-A,B 2184842	01-07-87
		JP-A- 62116227	27-05-87
		SE-B- 457830	30-01-89
		SE-A- 8604849	14-05-87
		US-A- 4770543	13-09-88

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82